

Optimal and Long-Term Dynamic Transport Policy Design: Seeking Maximum Social Welfare through a Pricing Scheme

ABSTRACT

This article presents an alternative approach to the decision-making process in transport strategy design. The study explores the possibility of integrating forecasting, assessment and optimization procedures in support of a decision-making process designed to reach the best achievable scenario through mobility policies. Long-term evaluation, as required by a dynamic system such as a city, is provided by a strategic Land-Use and Transport Interaction (LUTI) model. The social welfare achieved by implementing mobility LUTI model policies is measured through a cost-benefit analysis and maximized through an optimization process throughout the evaluation period. The method is tested by optimizing a pricing policy scheme in Madrid on a cordon toll in a context requiring system efficiency, social equity and environmental quality. The optimized scheme yields an appreciable increase in social surplus through a relatively low rate compared to other similar pricing toll schemes. The results highlight the different considerations regarding mobility impacts on the case study area, as well as the major contributors to social welfare surplus. This leads the authors to reconsider the cost-analysis approach, as defined in the study, as the best option for formulating sustainability measures.

Key Words: CBA approach, policy optimization, sustainable transportation, urban transport policy

1. INTRODUCTION

Sustainability has become a challenge for every city authority. Congestion, pollution, resource consumption, social exclusion, and deterioration of quality of life are some of the problems that authorities must deal with in the coming years due to the intensive and continuous growth of car usage.

There is an increasing range of policy measures available. However, this fact, added to the complexity of the city system as a dynamic environment and the ambitious concept of sustainability—which includes economic, environmental and social targets—has made it difficult to identify the measure or combination of measures that will enhance welfare.

The aim of this work is therefore to explore the possibility of integrating forecasting, analysis and optimization procedures in support of a decision-making process designed to obtain the best achievable scenario. The method is presented by means of the optimization of a simple pricing policy scheme.

Fiscal instruments are currently accepted both as mobility management measures for maintaining traffic at a reasonable level and as a way of internalizing externalities through direct payments (Rich and Nielsen, 2007). In addition, revenues can be ploughed back into transport systems in order to achieve greater efficiency (Ferrari, 2002) to improve the level of service of public transport (PT).

The objective of the measure to be optimized is generally proposed to be a mechanism for reducing the congestion existing in the central business district (CBD), as well as a reduction of the impact caused by this congestion (e.g., emissions, noise) on an area which is particularly sensitive due to the presence of a high density of population and commercial activities.

London implemented a congestion charge (zonal scheme) in the center of the city. This measure has succeeded in reducing traffic delays by 30% inside the city center due to a 15% reduction in traffic circulating within the zone, and an 18% reduction in traffic entering the central zone during charging hours (Leape, 2006). However, traffic speeds have now returned to approximately what they were before the scheme was introduced. In Stockholm, a cost-benefit analysis (CBA) based on the measured result of the charging trial in 2006 shows that the toll system yields a considerable social surplus net of investment and operational costs (Eliasson, 2009). In Norway, road tolling has primarily been considered as a practical measure to secure the necessary funding for roads, including those located in urban areas. Recent amendments to Norwegian law have included public transport—both infrastructures and operation—as the destination for funds raised through pricing policies (Lauridsen, 2011). There is also a demand for variable toll schemes depending on the level of congestion (Ramjerdi, Minken, and Østmoe, 2004).

Even though a charging scheme has proven successful for some cities, there is still the general problem of the transferability of experiences from one case to another (Rich and Nielsen, 2007). As a general assumption, the greater the congestion in the toll zone, the higher the benefits to be expected if car use can be reduced.

The most common scheme, applied in the London Congestion Pricing (Litman, 2006; Leape, 2006), Singapore Area License Scheme (Santos, Li, and Koh, 2004)

and the Norwegian toll rings (Lauridsen, 2011) is one that charges a fee for driving a vehicle through the charging zone. The manner in which and how the charges are applied may vary, depending on both policy and available technology.

Traditionally, city center pricing strategies are evaluated using a static CBA (Rich and Nielsen, 2007; Eliasson, 2009; Rotaris et al. 2010). However, this approach does not take into account that these schemes may have long-term impacts on urban activities and the dynamics of the interrelationship between residential and workplace patterns, in addition to the traditional patterns of changes in mobility. As these pricing policies may affect not only traffic flows and traveler behavior, but also various other elements of the urban environment such as housing and business location, traffic accident rate, air quality and greenhouse gas emissions, another kind of impact assessment framework is needed. Moreover, sustainable transport policies must be long term, with policies sustained over time, for lasting and real impact (Buehler and Pucher, 2011).

This article focuses on determining the optimum toll value for entering a defined area according to sustainability targets (maximum social welfare) and land-use and transport dynamics.

It is important to capture the dynamic character of these variables in relation to the target function and their future impact within the urban system. The road pricing policy reduces the effects of congestion, raising revenues for PT improvements and encouraging fewer and shorter trips, and the shifting of trips to off-peak periods. The theory of Systems Dynamics (SD) offers a good approach to simulate complex systems in the long term in both land-use and transport modeling. An SD approach helps to identify the ways in which causal mobility structures and travel behavior patterns rely on a formal simulation model to capture the full complexity of the metropolitan mobility situation, and to make more reliable inferences about travelers' behavior (Sterman, 2000).

There is little research on SD-based optimization in the literature. Some references offer material on the attempt to combine the optimization process with SD (Miller, 1998; Dangerfield and Roberts, 1999; Coyle, 2000; Timms, May, and Shepherd, 2002; Pfaffenbichler and Shepherd, 2003; Shepherd et al. 2006). In order to obtain an understanding of different transportation policies, a number of researchers have used the SD approach for transportation modeling. However, there is very limited research that evaluates the dynamic consequences of congestion pricing policies on a pricing area (Liu, Triantis, and Sarangi, 2010). This study provides a modeling framework based on the SD approach by which policy-makers can understand the dynamic and complex nature of traffic congestion within the representation of a socioeconomic transportation system in a metropolitan area.

Haghani, Lee, and Byun (2003a, 2003b) presented a SD model to study the interactions between transportation and land-use. This modeled performance as a policy tool and examined the impacts of highway capacity expansion over time. Qiang, Zhong, and Yuan (2006) used an SD approach to investigate traffic problems in Shanghai, and showed that road congestion will become more severe in the future if only road supply is increased.

Safirova et al. (2004) analyzed welfare and distributional effects using a detailed transport network model, representing metropolitan Washington, DC, area. Safirova et al. (2006) evaluated the long-term effects of a road-pricing policy based

on the integrated model of land-use, strategic transport and regional economy, and compared them with the short-term effects obtained from another model. Gupta, Kalmanje, and Kockelman (2006) explored the traffic, land-use and welfare impacts of road pricing in the Austin (Texas) region, introducing various road pricing simulations. On the other hand, Zhang et al. (2011) tackle with the problem of congestion pricing in multiple regions where each local administrative region sets its own toll levels using various bi-level models. Five pricing schemes were proposed considering competitive, cooperative, or mixed behaviors of both in regional road pricing and in general networks with two or more regions. None of these studies include an optimization process. However in Li et al. (2012), an optimization problem for designing an environmentally sustainable toll scheme is formulated. In this case, environmental externalities are incorporated to the congestion pricing in order to avoid environmentally unsustainable urban transportation systems. The method incorporates the effects of uncertain demand and supply into the road toll pricing models for policy assessment.

Once the SD theory is assumed in a Land-Use and Transport Interaction model (LUTI model), the goal is to establish a procedure for long-term optimization, with social welfare as an objective function (OF) and the toll fee as the variable to define. This goal is similar to other studies such as the works by Emberger, Shepherd, and May (2008), and Shepherd et al. (2006), which present optimal transport strategies resulting from the application of a single policy instrument. Madrid Metropolitan Area has been selected as appropriate case study, where implementing such a procedure helps to highlight the main features and impacts of a hypothetical toll ring scheme. It is a city with 5,867,299 million inhabitants (in 2004) with rather complex land-use and mobility patterns.

This article is organized as follows: the proposed methodology is outlined, and the LUTI model is briefly described. Then the optimization process and the OF are detailed. The second part shows the case study description, and the toll ring scheme optimization results are presented based on the case study. Main results obtained are synthesized. Discussions about the efficiency of the pricing policy, impacts generated and main contributor to the social welfare surplus reached are tackled.

2. THE PROPOSED METHODOLOGY

A system is defined as a group of entities which act and interact together towards the achievement of a specific target. This system may represent only a part or a subset of an overall system. This proposed SD approach consists of linking the subsystems of land-use and transport and an optimization procedure.

Figure 1 shows the interaction between all the sub-models, the policy instruments, and the optimization tool. The LUTI model and the optimization procedure are integrated by means of an OF, based on a dynamic CBA development. There is also a link between the optimization routine and the LUTI model through the transport policies. The intensity of the policy is changed in each iteration through the OF maximization seeking process.

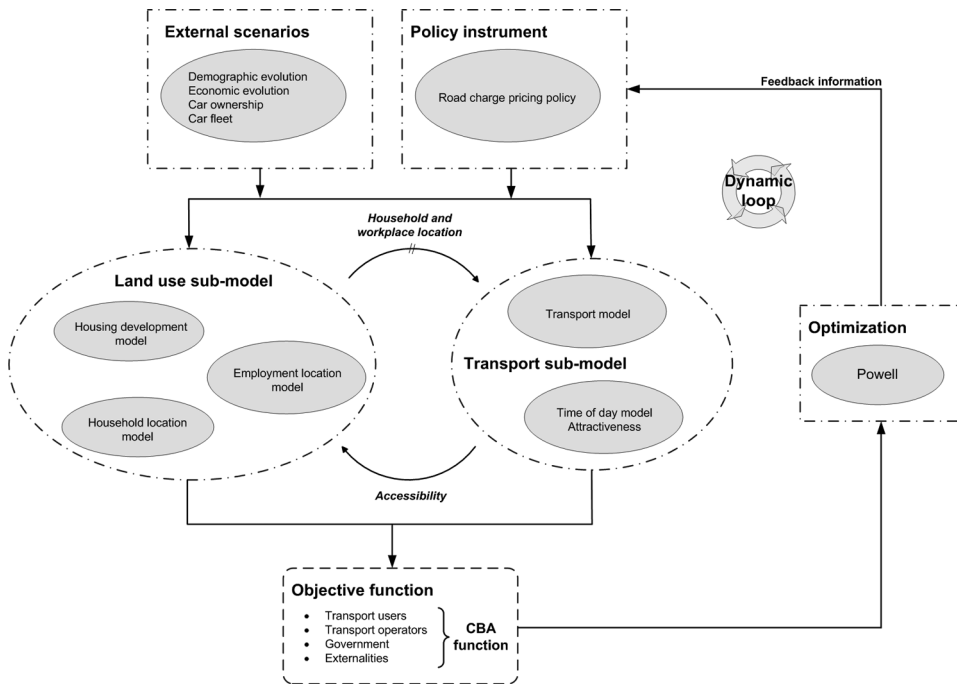


Figure 1. Dynamic long-term loop of the integrated process. Basic structure of the evaluation and optimization model.

3. THE LAND-USE AND TRANSPORT MODEL

A system is termed dynamic if its interactions cause changes over time, and is useful in evaluating long-term scenarios where the behavior to be assessed is the consequence of complex interactions.

The methodology is based in the use of a LUTI model. This land-use and transport system is considered to be a long-term SD. In this case a strategic, dynamic, and integrated urban land-use and transport model is used as the framework. The LUTI model has been calibrated for the regional and metropolitan area of Madrid. We have selected the MARS model (Metropolitan Activity Relocation Simulator) (Pfaffenbichler, 2008) because it fits quite well with the requirements of the case study and the complexity of the interaction among several transport modes and type of activities.

MARS was developed as a way to investigate strategic issues over a long time period. The average running time of MARS model is less than ten minutes for a 30-year simulation with quarterly time slots. The user is therefore able to test a wide variety of different policy instrument values and/or combinations in a reasonable time, allowing each scenario reached over the 30 years to be measured through a set of indicators. This information is needed to feed the welfare OF to be optimized. A full description of the MARS model is provided in Pfaffenbichler (2008).

The model includes a transport model, a housing development model, a household location choice model, a workplace development model, and a workplace location choice model, all of which are interrelated through causal-effect relations. MARS also includes a fuel consumption and emission model. Three composite modes are represented: car (driver and passenger), public transport (bus and rail) and slow modes (cycling and walking). This model uses the concept of a constant time budget (Levinson and Kumar, 1994). Commuting trips are assumed to be inelastic, and therefore off-peak journeys increase as peak-time congestion falls (Emberger et al. 2008). Table 1 shows the main characteristics of MARS.

The MARS model structure is based on a concept of causal loop diagrams (CLD) as shown in Figure 2. Each of the diagrams identifies the cause-effect relationship among different variables (e.g., “car commute trips” depends on some variables like “employed population” and “car attractiveness,” and it contributes to others as “car speed”). There are two types of loops: balancing and reinforcing. Attractiveness depends on availability, costs, and times, not only for the car but for the other modes of transport as well. But at the same time, attractiveness varies according to the intensity of car usage, as congestion may balance the time used for car trips in relation with the other modes (L1: balancing causal loop). On the other hand, congestion may also affect PT performance which can improve car attractiveness, in this case configuring a reinforcing loop (L3). This must be added to a third loop (balancing loop L2), as fuel consumption is related to travel speed. Similar configurations can be extended through all the subsystems, establishing a complex system of interrelated variables (Pfaffenbichler, Emberger, and Shepherd, 2008).

Table 1. Main characteristics of the metropolitan activity relocation simulator (MARS) model.

Model feature		MARS
Number of zones	90 zones	
Modes of travel	Yes	
Congestion effects	Car, public transport, slow	
Generalized costs	OD-specific speed-flow curves for commute trips. No speed effect for other trips (assumed to be off-peak)	
Journey purposes	In-vehicle time, money, access/egress time, parking search time, wait times, change times	
Time periods	Commute, other	
Levels of car-ownership	Peak, off-peak	
Demographics/ household categories	0 (no car); 1 (car available)	
Route choice	Average household size, employed residents, car per head, average income per zone	
Mode/destination choice	No	
Time of day choice	Simultaneous	
Demand response	No	
Land-use response	Commute trips inelastic, constant time budget	

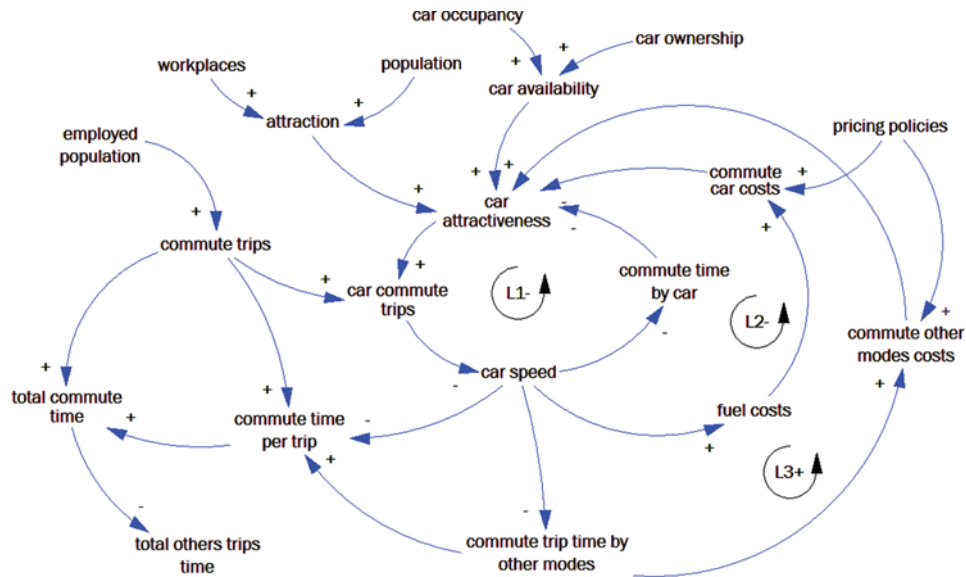


Figure 2. Causal loop diagram for commute car trips. (Figure appears in color online.)

In this case, pricing policies may alter this equilibrium reached through the different causal loops as car attractiveness is modified. It is this simple causal loop structure and user-friendly software (Vensim[®]) that helps improve the transparency, and hence the usefulness, of the modeling approaches used.

Furthermore, MARS assumes that land-use is not a constant but is rather part of an SD that is influenced by transport infrastructure (Shepherd et al. 2006). The interaction process is modeled using time-lagged feedback loops between the transport and land-use sub-models over a 30-year period. The basis of the stock-flow diagram for the expanded SD model is reproduced in Pfaffenbichler (2008). Thus accessibility changes in the long term, influencing both residential and workplace locations. The intensity of the change is directly related to the intensity of the measure (de la Hoz et al. 2008).

3.1. The Proposed Optimization Process

The optimization model enables the level of intensity of the application of certain transport policies to be defined.

Optimization techniques have been an important field of research in transportation planning (May, Shepherd, and Timms, 2000; Mayhew and Hyman, 2002; de Palma, Kilani, and Lindsey, 2005; Vold, 2005; Shepherd et al. 2006; Zhang et al. 2006; Emberger et al. 2008; Light, 2009). However, the assessment of these techniques and their successful implementation in real-world transport cases remains to be validated.

In this work Powell's optimization method (Powell, 1964) will be applied. This method is an algorithm that searches for a local minimum/maximum of objective

function for a set of linearly independent direction vectors without calculating the derivatives. A detailed discussion of the algorithm is given in Brent (1973), and the complete algorithm is given in Press et al. (2007).

This method can be applied to optimize several types of transport and land-use policies; however in this case, the optimization process to choose the best transport policy levels is proposed with an application with two variables: a toll-pricing policy (short and long term) for passenger vehicles in Madrid city center. Examples of optimization of transport policies employing other methodologies can be found in Mayhew and Hyman (2002), Shepherd et al. (2006), Zhang et al. (2006), and Li et al. (2012).

3.2. The Objective Function

Traditionally, pricing policies are assessed in a discrete way and analyzed within a single period of time. However, effective planning requires making a long-term evaluation.

The welfare function is defined as the social benefits obtained throughout the complete period of time; however, the objective function must offer a judgment about the strengths of the scenario evaluated. This means that a scenario of reference is needed.

Thus the objective function (OF) showed in Eq. (1) measures the change in social welfare compared to the A0 scenario, (do-nothing, reference scenario). This function is defined by the following elements: the change in consumer surplus (ΔCS_{ij}), which includes both the money costs (or savings) and time savings for the users, resulting from the implementation of strategy X . The operator change benefits (ΔO_{ij}) include gains linked to revenues from fares and charges. The government change benefits (ΔG_{ij}) include fuel tax revenues, and savings on road costs through decreased maintenance. Finally, the externalities change benefits (ΔE_{ij}) include those derived from reductions in the accident rate, as well as lower greenhouse gas emissions and the health benefits of the resulting better air quality (NOx and PM₁₀).

$$OF = \sum_{t=0}^{30} \sum_{ij} \left[\frac{1}{(1+r)^t} \right] \cdot [\Delta CS_{ij}(t) + \Delta O_{ij}(t) + \Delta G_{ij}(t) + \Delta E_{ij}(t)] \quad (1)$$

The final evaluation includes the analysis of the OF expressed by net present value (NPV) over the full time horizon, and using a discount social rate of $r=4.8\%$ (Souto Nieves, 2003). The variable t represent the period of time. The i and j subscripts refers to origin and destination zones, respectively.

The cost unit values for externalities (and Tables 2 and 3) were obtained from the European Project “Developing Harmonized European Approaches for Transport Costing and Project Assessment” (Bickel et al. 2005). As shown in the above equation, the investment costs are not taken into account.

In order to obtain a framework able to assess a multimodal transport system, it is necessary to have a dynamic CBA based on a benefits distribution by transport mode and by origin, according to the approach advocated in Sugden (1999). The disaggregated welfare function for the transport users (consumer surplus,

Table 2. Estimated emissions values and casualties avoided.

Estimated emissions value			
Year	Avg. CO ₂ value	Avg. NOx value	Avg. PM ₁₀ value
2004–2009	22	5.300	2.873
2010–2019	26		
2020–2029	32		
2030–2039	40		
2040–2049	55		
2050	83		
Estimated casualties avoided			
Fatality	Severe injury	Slight injury	
1.193.686	147.755	11.171	
2004 prices (€/t).			
2004 prices (€).			

CS) is given by Eq. (2):

$$\Delta CS = \frac{1}{2} \sum_t \sum_{ijm} (T_{ijm}^0 + T_{ijm}^1) \cdot \left[(t_{ijm}^0 - t_{ijm}^1) + ((c_{ijm}^0 + \tau_{ijm}^0) - (c_{ijm}^1 + \tau_{ijm}^1)) \right] \quad (2)$$

Where T_{ijm} is the demand for trips between i and j by mode m ; t_{ijm} is travel time multiplied by the value of time; c_{ijm} is operational mode costs (fuel + fixed costs) and finally τ_{ijm} is the costs corresponding to fares, parking fees and other charges. The superscript k is used to denote both the do-nothing scenario ($k=0$) and the alternative scenario ($k=1$).

In the square brackets in Eq. (2), the first term (*travel time*) is the value of time gains once the charges are in place. The second and third term (*operating costs, fares*

Table 3. Features of Study Zone.

	Tolled zone CBD	Rest of periphery	Modeled metropolitan ring	Area regional ring	Modeled area total
Population	1.010.545	2.142.759	1.992.333	712.662	5.867.299
Workplaces	877.695	563.833	587.450	186.826	2.215.804
Area [km ²]	41,8	562,2	2.272,6	5.151,7	8.031,4
Modal split (PT/PC) [%]	71/29	55/45	31/69	13/87	55/45
Car/1.000 inhabitants	450	379	525	506	510

Note. Data year 2004 (last mobility survey in Madrid); PT = public transport; PC = private car.

and charges) provides estimates for the savings on car operating costs, basically the cost of fuel; and shows the revenues from the system. This is the disaggregated function for the transport users. The value of time assumed was 10.45 €/h for commuting trips and 5.70 €/h for other trips (Monzón, Fernandez, and Jordá, 2008).

Equation (3) shows the value of net benefits to operators, including PT fares and toll and parking charges, calculated over a 30-year time period, but ignoring initial infrastructure costs. This equation includes the parking operator, the toll operator and the PT operator. Equation (4) represents the government's benefits or losses resulting from changes in fuel tax revenue (ΔF_{ij}) and changes in the cost of road maintenance (ΔM_{ij}). Finally, equation (5) represents the value of externalities, associated with green-house gas emissions (ΔGHE_{ij}), air pollution (ΔP_{ij}) and safety (ΔS_{ij}).

i. Operators benefits:

$$\sum_t \sum_{ijm} T_{ijm}^1 \cdot (\tau_{ijm}^1 + c_{ijm}^1) - T_{ijm}^0 \cdot (\tau_{ijm}^0 + c_{ijm}^0) \quad (3)$$

ii. Government benefits:

$$\sum_t \sum_{ijm} (T_{ijm}^1 - T_{ijm}^0) \cdot (F_{ijm} + M_{ijm}) \quad (4)$$

iii. Externalities benefits:

$$\sum_t \sum_{ijm} (T_{ijm}^1 - T_{ijm}^0) \cdot (GHE_{ijm} + P_{ijm} + S_{ijm}) \quad (5)$$

According to our calculations, the value of operating costs (c_{ijm}) and travel time (t_{ijm}) by mode will depend on each OD pair (distance and travel time). The operating costs by mode could vary depending on the scenario, as the destination zone change may be due to higher travel costs. Accounting for these in operating and travel time costs helps to improve the accuracy of estimates of consumer surplus, since travelers with higher time costs may choose to make shorter trips or use cheaper modes. Therefore, the CS can be rewritten by separating it into these component terms -commuting and other mobility- by modes of transport m .

3.3. Madrid Case Study

The congestion charge was applied to the CBD of Madrid as shown in Figure 3. The toll area is about 41.8 km². Table 4 shows the basic information of the modeled area. According to Madrid 2004 mobility survey (CRTM, 2004), there are some 250,000 car travelers living inside the tolled area (CBD) who work outside,

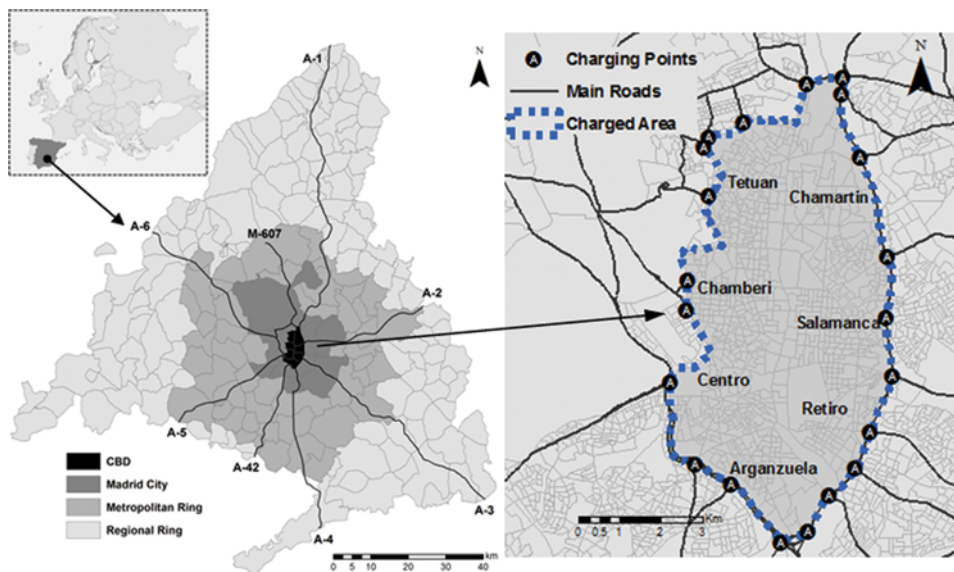


Figure 3. Study area – Madrid. (Figure appears in color online.)

Table 4. Surplus A1/A0 of the Madrid road charge scheme for the optimal toll value [NPV M€].

Category	Sub-category	Time savings	Operation costs	Other costs	Savings/monetary expenses	Total
Car	Vehicles (PH)	+180,5	+13,4	-911,0		-717,1
	(VH)	+0,9	-0,1			+0,6
Public transport	Passengers (PH)	+97,6				+97,6
	(VH)	+0,2				+0,2
Government	Fuel duty				-28,6	-28,6
	Road maintenance				+2,9	+2,9
Operators	Parking revenues				-132,7	-132,7
	Toll revenues				+872,5	+872,5
	Fare revenues				+22,0	+22,0
Externalities	Accidents			-12,2		-12,2
	CO ₂			+5,3		+5,3
	NOx and PM ₁₀			+1,5		+1,5
Total		+279,2	+13,3	-916,5	+736,0	+112,0

Note. PH = Peak hour; VH = Off-peak hour.

and similar number—260,000—that live outside and have their workplaces inside the CBD.

The MADRID MARS model represents the area mentioned above, with 90 zones covering the whole province (modeled area).

The toll scheme modeled presumes that tolls are charged automatically to drivers as they pass, without stopping, through several toll barriers located at the contours of the charged area (dotted line). It is also assumed that the toll-road user will pay the same toll regardless of the car type or the residential zone in which he or she lives.

Costs of installing and operating the toll scheme in Madrid are not considered in this study because it would be necessary to design the implementation project which is not the scope of this article. However the Madrid toll ring would be implemented in the existing motorway that has been fully equipped in 2007 with access control gates, management control center, etc. Therefore the extra costs associated to toll management could be rather low if the system operates with modern electronic tags.

On the other hand, a parking fee is currently imposed in the CBD, including for residents. For the sake of simplicity in the discussion, this fee is maintained constant (€2.50) and is estimated as an average of the current parking costs assumed by citizens.

Taking as a reference the 1996 and 2004 mobility surveys, it can be seen (Guzmán and de la Hoz, 2009) that trips inside the Madrid district lose weight in the overall figures: from 57.1% to 48.6% between 1996 and 2004, respectively. At the same time, the outermost trips, radial trips between the external rings, and orbital trips within the rings are those that grow most in relative terms.

However from a global point of view, the relative weight of mobility to the center-radial mobility- has gradually decreased in recent years in Madrid. A significant change can be seen in the period from 1996–2004; the metropolitan ring has grown in importance (see Figure 4), as a result of the dispersal of activities. This has major effects on the modal distribution and efficiency of the system, given that the greatest growth occurs precisely in those relationships where the car is the primary mode of transport.

3.4. Scenarios

The reference scenario (A0) includes only the infrastructures built in 2004 and does not consider any intervention during the 30-year evaluation period (2004–2034). Under scenario A0, the net social welfare is set to zero. The optimum toll value obtained in the alternative scenario A1 that maximizes the NPV of the OF proposed is the surplus of the social welfare compared to scenario A0.

When the optimization procedure is defined, we assume that in the most general case the pricing policy can be applied to any time-period of assessment ($t = 1, 2 \dots 30$). In this case, for a single instrument there could in theory be 30 different levels in the optimal solution. However, and according to Emberger et al. (2008), we have not attempted to solve this problem as the optimal policy must be easily understood, and easy to present to decision makers.

In this case, two variables have been used in the optimization procedure: an optimum toll value for the short term (2010) and another for the long term

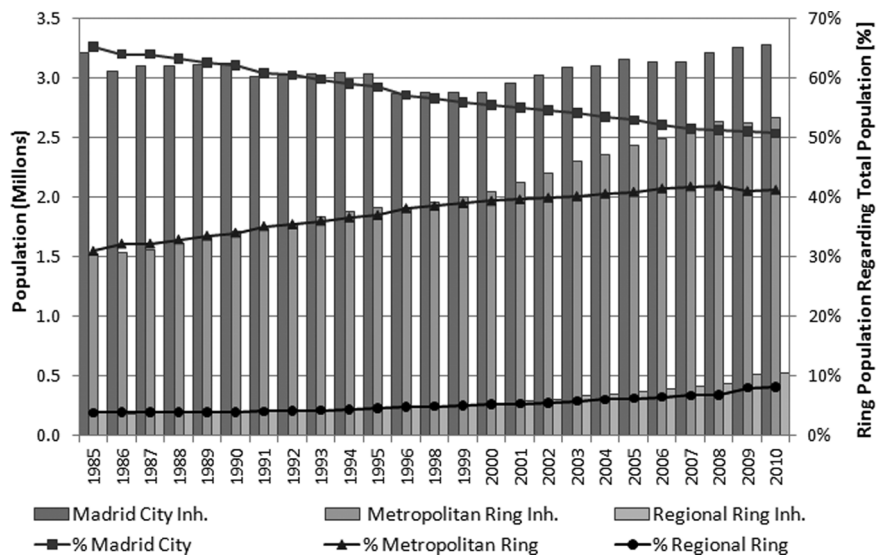


Figure 4. Evolution of the population (by rings) in Madrid Region.

(2034). We assume the toll increases linearly between the toll level selected for 2010 and 2034. Additionally, the toll ring policy is optimized for two periods of the day: peak and off-peak. The toll scheme is implemented only for passenger vehicles. The base-line year for this study is 2004 and the toll ring scheme is assumed to be implemented in 2010.

External variable projections such as economic and population growth are estimated based on data for official statistics (from the Madrid Institute of Statistics; INE, 2010).

4. SUMMARY OF RESULTS

The assessment provides an overview of the effects of the toll ring scheme, and the main results obtained indicate that certain pricing policies (or a combination of them) could be very useful for the city over the long term.

The estimation results for optimal values are reported in Figure 5 and are based on welfare NPV during the whole evaluation 30-year period. As we can see, the toll value optimum for the Madrid Case Study presented is €1.0 for the start value in the year 2010, and €2.0 for the last value in 2034; for the peak period. However, the fee for the off-peak period is zero.

The proposed toll value in off-peak periods in this study is zero because there is no significant congestion situation, coinciding with the results presented in May, Kelly, and Shepherd (2006) and Shepherd et al. (2006). Therefore, achievable potential time saving, which is the most relevant factor in a CBA analysis (Salling and Leleur, 2011), through pricing policies is so low that the optimal value reached for the tolling scheme is close to zero. However, in May et al. (2006)

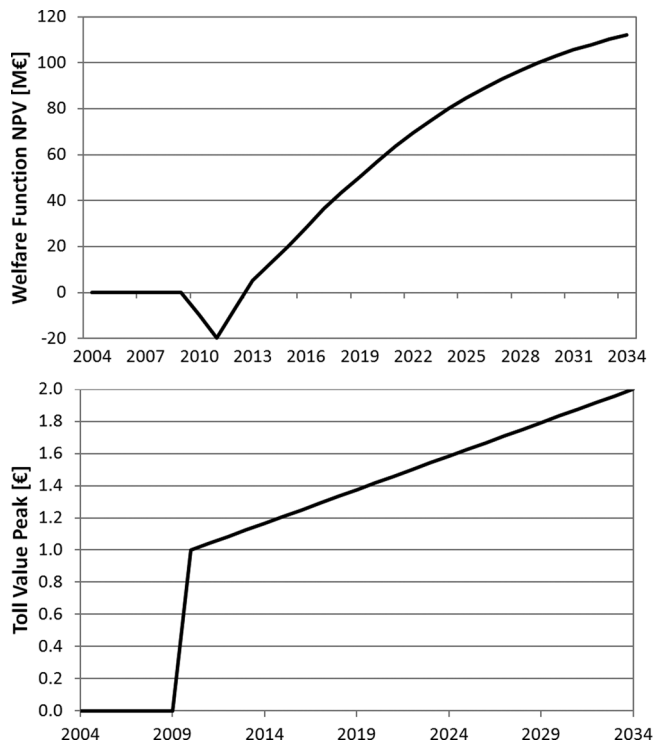


Figure 5. Social welfare and optimal toll value during peak period.

and Shepherd et al. (2006), optimum road charge value for peak period is 5€, but the off-peak road charges are set at 2€ (fixed value instead of optimal value).

As shown in, the implementation of a toll policy produce an immediate drop in social welfare. This is due to the period of adaptation of the mobility patterns to the measure implemented. Although the cost of the measure has an immediate effect on the generalized cost—and therefore on citizen behavior—the variations in transport time deriving from the new network situations undergo a different rebalancing process, as they depend on the demand existing in each system.

This means that citizens take a period of time to adapt to the new situation of the system. This period of adaptation is considered to be one year. This has direct implications on the assessment of annual welfare surplus, as the citizens assume the cost immediately but only perceive the benefits deriving from the greater capacity of the transport system after some delay, when the system has once again found a new equilibrium.

As it was expected, car traffic entering the cordon zone is reduced at the end of the time period by 9%, during charging hours. As can be seen in Figure 6, there is a modal shift from car to PT in radial trips (periphery to center) of around 3%. This modal shift results in a PT fare revenue surplus of 22.0 M€. In addition, the capacity surplus produces a scenario with less congestion in radial corridors. The speed increase not only affects car users, but also extends to road-shared

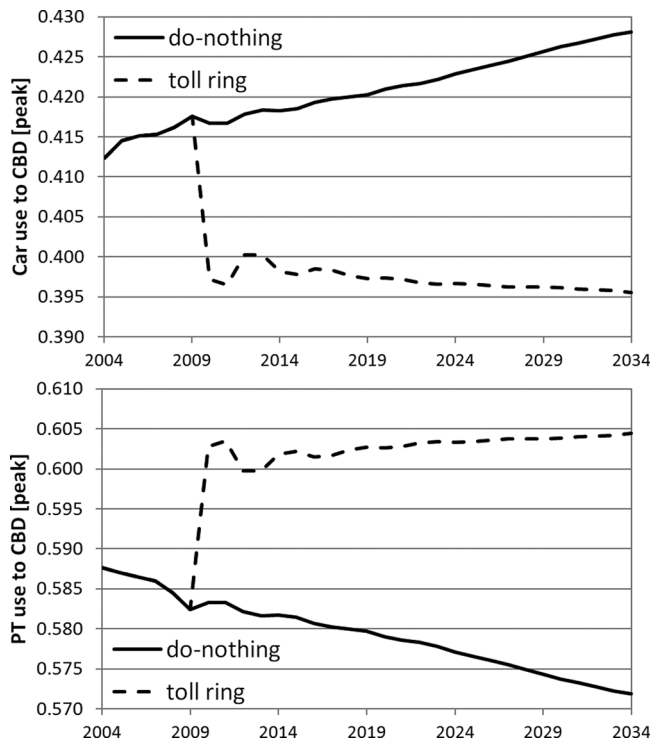


Figure 6. Percentage of car and PT trips among all motorized trips entering CBD.

PT services. This produces time savings to PT users of €97.6 M€. However, 6% of radial car trips have changed their destination pattern, intensifying the loss of attractiveness of the CBD (see Figure 6) compared to the rest of the region.

In the case of internal CBD mobility, this scenario produces a reduction of the use of roads in the city center that reduces delays by 3%. The main consequence is more car usage by CBD residents excluded from toll charging. These dynamics may require an adaptation of the tolling scheme (it is not unusual for pricing policies to change over time; Leape, 2006) or it may need to be complemented with other transport policies, such as a new parking scheme.

In Table 5, the net present value from costs and benefits (welfare surplus regarding scenario A0) generated by the Madrid city center road charge are presented within the framework described above. It is important to highlight the significant time savings, and even more so compared to the costs of externalities linked to environmental impact (pollution and CO₂ emissions). The increase in the accident rate caused by speed increases in the charging area leads to higher accident costs.

Revenues from fuel duties are reduced due to the decrease in car use, even though the average distance traveled by car is higher, but this demand (in veh · km) increase is much less than the veh · km saved with the reduction of

trips. Fuel consumption per kilometer decreases because speed increases within the range where fuel consumption is still a decreasing function of speed. Car usage reduction (veh · km saved) implies a lower road maintenance cost (+2.9 M€), and this, added to the higher fuel consumption efficiency, generates a reduction in fuel duty incomes for Government.

NPV obtained is highly dependent on social discount ratio (4.8%). This ratio is higher to discount ratios assumed in UK (3.5%; Shepherd et al. 2006). This means that long-term potential benefits are underestimated against short-term, which may jeopardize final social welfare surplus if costs of construction and maintenance are included in the analysis with a 4.8% discount rate. The study presented hasn't optimized the objective function with a finance constraint, though this may be possible.

Even though main objective of the toll scheme is not to collect money but to reduce car pressure and congestion in the center, the pricing policy generates a significant positive present value of finance (+736 M€) which may lead to promote complementary measures. This integrated strategies may generates benefits greater than the sum of their individuals (May et al. 2006).

As this measure has been implemented locally within the Madrid region (0.52% of the total area of Madrid and 25% of the total motorized trips), the impact on land-use patterns (housing and workplace response) is fairly limited, and its impact is almost unnoticeable.

The results obtained show the relatively minor importance of environmental externalities compared to the social costs (accidents) and time-saving benefits using a CBA approach. This approach may therefore not be the most appropriate method for urban transport policy planning under a sustainability framework (Sato and Lan, 2007). The results obtained from this approach do not lead to a sustainable scenario when the efficiency of the network is a priority.

5. CONCLUSIONS

The proposed method stems from the need of transport policy decision-makers to establish the best strategy to be implemented in order to maximize the city's welfare. The process described involves fixing an appropriate toll charge to be assigned in an urban cordon charge scheme in order to maximize social welfare.

The optimal toll charge is estimated in terms of the potential social surplus imposed on users, administration or externalities, compared with the alternative do-nothing scenario over a period of 30 years. Land-use and transport dynamics are also considered.

Powell's direct optimization method has proved to be an adequate and rapid convergence method for the problem tackled. The benefits of this method are its easy integration with the model, its rapid convergence and the fact that it does not require explicit computation of the function's gradient (Press et al. 2007), which is unavailable due to the complexity of the OF. The results show that the optimization process is robust and can be applied to different objectives.

The results obtained in the optimization process show that a pricing policy for car users may generates significant net gains. The optimal toll ring value estimated is significantly lower than in other toll schemes.

Comparison to other CBA results directly is not possible as the models were set up with different study areas and different populations. Pricing policies are therefore applied to different populations. Added to above, net present value obtained is highly dependent on social discount rate. In this exercise, a rate of 4.8% was implemented, notably higher than other studies where a 3.5% discount rate was taken (Leape, 2006; Shepherd et al. 2006; May et al. 2006). On the other hand, main contribution to positive welfare on a CBA approach is trip time saved. Thus, lower value of time assumed compared to UK's models may lead to a lower congestion charge.

However, common results are obtained with the introduction of road charging schemes: car users journey times are reduced, public transport users and public transport authority are beneficiaries as well.

Thus, result obtained confirms the objectives pursued by the measure: low car use in sensitive areas such as the CBD. However, in the absence of complementary measures, other impacts should be considered: for example there is an increase in internal mobility by car due to the capacity released by citizens who have ceased to travel by car to the CBD. This effect is largely limited by the fact that these are areas of high accessibility and service by public transport, but in any case it is the substitution effect which it would be useful to consider. In the same way, there is zonal redistribution of trips towards the peripheral areas. Transversal and orbital mobility increases compared to radial mobility. This effect, although limited, induces a mobility which -in view of the configuration of the transport system in Madrid- is not susceptible to being captured by the collective transport system.

Another point to highlight is that there is an increase in speed in the road transport system due to the reduction in congestion. This not only has an effect on car users but also on public transport users who share the roads with cars.

We have assumed that the location of the toll ring scheme is the best, however other studies have demonstrated that the performance of cordon schemes is critically dependent on cordon location (May et al. 2002); although, this is another optimization problem, that is beyond the scope of this article.

The greatest social benefits appear to be linked mostly to decreased congestion, and to the revenues generated which can be allocated to the improvement of other aspects of transportation. Environmental aspects are not assigned a significant value under the optimum scenario, which may indicate that the assessment method and the CBA-based objective function prioritize the efficiency of the network itself, rather than other aspects of sustainability (social and environmental issues). This suggests that further research should be undertaken in order to define a better OF that will allow for the attainment of scenarios deemed more sustainable.

To achieve this, further research should focus partially on improving the CBA assessment approach for the OF. A multicriteria analysis (MCA) approach appears to represent a step forward in making the optimization model correspond more closely to the sustainability principle, according to the dimensions of socially sustainable urban transportation described in Boschmann and Kwan (2008).

There is also a need for further research which takes into account the potential differences in social welfare optimization if short-run and long-run optimal toll values are independent. Currently, the toll scheme policy is optimized for the

entire period of evaluation, although the measure is defined by a start and ending value. This means that the total social surplus achieved every year is taken into account. Making each period of time independent can generate a different policy configuration than the one currently obtained.

Finally, the results obtained show that other transport and mobility management measures should be coordinated and implemented with the toll scheme in order to obtain higher levels of sustainability, especially when the measures implemented generate an income surplus for the transport operators.

In view of this, the optimization process presented should also be applied to define not just an isolated measure (toll ring scheme) but the optimum level of an entire group of different measures which may generate important synergies for reaching sustainable scenarios. Without questioning the fact that to achieve efficiency, car users should pay for the true costs of their actions (such as pollution or congestion taxes), we have found sufficient evidence in the literature to demonstrate that many other policy instruments can be used in combination with taxes and permits to ensure that the transport needs of the present generation can be met without compromising the ability of future generations to meet any needs of their own (Santos, Behrendt, and Teytelboym, 2010).

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